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Discovering the Higgs Bosons of Minimal Supersymmetry with Muons and a Bottom Quark

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Abstract

We investigate the prospects for the discovery at the CERN Large Hadron Collider of a neutral Higgs boson produced with one bottom quark followed by Higgs decay into a muon pair. We work within the framework of the minimal supersymmetric model. The dominant physics background from the production of $b\mu^+\mu^-$, $j\mu^+\mu^-, j = g, u, d, s, c$, and $b\bar{b}W^+W^-$ is calculated with realistic acceptance cuts. Promising results are found for the CP-odd pseudoscalar (A^0) and the heavier CP-even scalar (H^0) Higgs bosons with masses up to 600 GeV. This discovery channel with one energetic bottom quark greatly improves the discovery potential of the LHC beyond the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$.

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I. Introduction

In the minimal supersymmetric standard model (MSSM) [1], the Higgs sector has Yukawa interactions with two doublets ϕ_1 and ϕ_2 that couple to fermions with weak isospin $-1/2$ and $+1/2$ respectively [2]. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of singly charged Higgs bosons $H^\pm$, two neutral CP-even scalars H^0 (heavier) and h^0 (lighter), and a neutral CP-odd pseudoscalar A^0. The Higgs potential is constrained by supersymmetry such that all tree-level Higgs boson masses and couplings are determined by just two independent parameters, commonly chosen to be the mass of the CP-odd pseudoscalar (m_A) and the ratio of vacuum expectation values of neutral Higgs fields ($\tan\beta \equiv v_2/v_1$).

At the CERN Large Hadron Collider (LHC), gluon fusion ($gg \to \phi^0, \phi^0 = h^0, H^0$, or A^0) is the major source of neutral Higgs bosons in the MSSM for $\tan\beta$ less than about 5. If $\tan\beta$ is larger than 7, neutral Higgs bosons are dominantly produced from bottom quark fusion $b\bar{b} \to \phi^0$ [3–7]. Since the Yukawa couplings of $\phi^0 b\bar{b}$ are enhanced by $1/\cos\beta$, the production rate of neutral Higgs bosons, especially the A^0 or the H^0, is enhanced at large $\tan\beta$.

For large $\tan\beta$, the $\tau\bar{\tau}$ decay mode [8,9] is a promising discovery channel for the A^0 and the H^0 in the MSSM. The LHC discovery potential of the inclusive muon pair channel for neutral Higgs bosons of minimal supersymmetry was demonstrated by Kao and Stepanov [10,11], and was later confirmed by the ATLAS collaboration [12]. In the minimal supergravity unified model [13], the significance of $pp \to \phi^0 \to \mu^+\mu^- + X$ is greatly improved by a large $\tan\beta$ [14] because the large $b\bar{b}\phi^0$ couplings make m_A and m_H small through the evolution of renormalization group equations [15].

For a Higgs boson produced along with one bottom quark at high transverse momentum (p_T), the leading-order subprocess is $bg \to b\phi^0$ [16–19]. If two high p_T bottom quarks are required in association with a Higgs boson, the leading order subprocess should be $gg \to b\bar{b}\phi^0$ [3,20–23].

Recently, it has been suggested that the search at the LHC for a Higgs boson produced along with a single bottom quark with large p_T should be more promising than the production of a Higgs boson associated with two high p_T bottom quarks [18]. In this letter, we present the prospects of discovering the MSSM neutral Higgs bosons produced with a bottom quark via Higgs decays into muon pairs. We calculate the Higgs signal and the dominant Standard Model (SM) background of $b\mu^+\mu^-, b = b$ or $\bar{b}$, with realistic cuts and compare its discovery potential with that of the inclusive final state of $pp \to \phi^0 \to \mu^+\mu^- + X, \phi^0 = H^0, h^0, A^0$. This discovery channel with one energetic bottom quark greatly improves the discovery potential beyond the reach of not only the associated mode with two bottom quarks $pp \to b\bar{b}\phi^0 \to b\bar{b}\mu^+\mu^- + X$ [20] but also the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$.

II. The production cross sections and branching fractions

We calculate the cross section at the LHC for $pp \to b\phi^0 + X$ ($\phi^0 = H^0, h^0, A^0$) via $bg \to b\phi^0$ with the parton distribution functions of CTEQ6L1 [24]. The factorization scale is chosen to be $M_H/4$ [6,25]. In this letter, unless explicitly specified, b represent a bottom quark (b) or an anti-bottom quark ($\bar{b}$). The bottom quark mass in the $\phi^0 b\bar{b}$ Yukawa coupling is chosen to be the NLO running mass $m_b(\mu_R)$ [26], which is calculated with $m_b(\text{pole}) = 4.7$ GeV and the NLO evolution of the strong coupling [27]. We have also taken the renormalization scale to be $M_H/4$. This choice of scale effectively reproduces the effects of next-to-leading order

(NLO) [18]. Therefore, we take the K factor to be one for the Higgs signal.

The cross section for $pp \to b\phi^0 \to b\mu^+\mu^- + X$ can be thought of as the Higgs production cross section $\sigma(pp \to b\phi^0 + X)$ multiplied by the branching fraction of the Higgs decay into muon pairs $B(\phi^0 \to \mu^+\mu^-)$. (In reality we integrate over a $\mu^+\mu^-$ invariant mass bin centered on m_ϕ.) When the $b\bar{b}$ mode dominates Higgs decays, the branching fraction of $\phi^0 \to \mu^+\mu^-$ is about $m_\mu^2/3m_b^2(m_\phi)$ where $m_b(m_\phi)$ is the running mass at the scale m_ϕ. This results in a branching fraction for $A^0 \to \mu^+\mu^-$ of approximately 3×10^{-4} for $m_A = 100$ GeV. For $\tan\beta \gtrsim 10$ and $m_A \gtrsim 125$ GeV, the cross section of bA^0 or that of bH^0 is enhanced by approximately $\tan^2\beta$; the muon branching fraction is sustained by the large decay width of the Higgs into bottom quarks.

III. The Physics Background

The dominant physics backgrounds to the final state of $b\mu^+\mu^-$ come from $bg \to b\mu^+\mu^-$ ($b\mu\mu$) as well as $gg \to b\bar{b}W^+W^-$ and $q\bar{q} \to b\bar{b}W^+W^-$ ($bbWW$) followed by the decays of $W^\pm \to \mu^\pm\nu_\mu$. In our analysis, we actually evaluated $gg \to b\mu^+\nu_\mu\bar{b}\mu^-\bar{\nu}_\mu$ and $q\bar{q} \to b\mu^+\nu_\mu\bar{b}\mu^-\bar{\nu}_\mu$ whose dominant contribution is from $pp \to t\bar{t} \to bW^+\bar{b}W^- + X$. In addition, we have included the background from $bg \to b\mu^+\nu\mu^-\bar{\nu}$ and $\bar{b}g \to \bar{b}\mu^-\bar{\nu}\mu^+\nu$ which has major contributions from $bg \to tW^-$ and $\bar{b}g \to \bar{t}W^+$ (tW). The cross section of the tW background is approximately 1/10 that of $bbWW$. The muons from b decays can be removed effectively with isolation cuts [10]. We have applied a K factor of 1.3 for the $b\mu\mu$ background [28], a K factor of 2 for $bbWW$ [29,30], and a K factor of 1.5 for tW [31]. The Feynman diagrams for $bg \to b\mu^+\mu^-$ are shown in Fig. 1. We have also considered backgrounds from $pp \to j\mu^+\mu^- + X, j = g, q$ or $\bar{q}$ with $q = u, d, s, c$, where a jet is mistagged as a b; we use a K factor of 1.3 for these processes.

In every event, each of the two isolated muons is required to have $p_T(\mu) > 20$ GeV and $|\eta(\mu)| < 2.5$. For an integrated luminosity (L) of 30 fb^{-1}, we require $p_T(b, j) > 15$ GeV and $|\eta(b, j)| < 2.5$. The b-tagging efficiency (ϵ_b) is taken to be 60%, the probability that a c-jet is mistagged as a b-jet (ϵ_c) is 10% and the probability that any other jet is mistagged as a b-jet (ϵ_j) is taken to be 1%.

For a higher integrated luminosity of 300 fb^{-1}, we require the same acceptance cuts as for $L = 30$ fb^{-1} except for $p_T(b, j) > 30$ GeV and $\epsilon_b = 50\%$. In addition, to reduce the background from $bbWW$ and tW which contains neutrinos, we require that the missing transverse energy ($\not{E}_T$) in each event should be less than 20 GeV for $L = 30$ fb^{-1} and less than 40 GeV for $L = 300$ fb^{-1}.

We have employed the programs MADGRAPH [32] and HELAS [33] to evaluate the background cross sections of $pp \to b\mu^+\mu^- + X, j\mu^+\mu^- + X$ and $bbW^+W^- + X$. The background from bbW^+W^- are treated with special care for $b-$tagging. If there is only one b passing the cuts, the cross section is multiplied with ϵ_b. For the events with two b's passing the cuts, we multiply the cross section with $2\epsilon_b - \epsilon_b^2$.

We have compared the prospects of detecting this Higgs signal with one high p_T bottom quark ($pp \to b\phi^0 \to b\mu^+\mu^- + X$) with that of the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$ and the associated discovery mode with two high p_T bottom quarks $pp \to b\bar{b}\phi^0 \to b\bar{b}\mu^+\mu^- + X$. The associated Higgs signal $b\bar{b}\phi^0 \to b\bar{b}\mu^+\mu^-$ has major physics background from $pp \to b\bar{b}W^+W^- + X$, $pp \to b\bar{b}\mu^+\mu^- + X$, and $pp \to jj\mu^+\mu^- + X$ [20]. The dominant physics background to the inclusive final state of $\mu^+\mu^-$ comes from the Drell-Yan process $q\bar{q} \to Z, \gamma \to \mu^+\mu^-$ [10].

IV. The Discovery Potential at the LHC

To study the discovery potential of $pp \to b\phi^0 + X \to b\mu^+\mu^- + X$ at the LHC, we calculate the background from the SM processes of $pp \to b\mu^+\mu^- + X$ in the mass window of $m_\phi \pm \Delta M_{\mu^+\mu^-}$ where $\Delta M_{\mu^+\mu^-} \equiv 1.64[(\Gamma_\phi/2.36)^2 + \sigma_m^2]^{1/2}$ [12]. Γ_ϕ is the total width of the Higgs boson, and σ_m is the muon mass resolution which we take to be 2% of the Higgs boson mass [12]. The CMS mass resolution will be better than 2% of m_ϕ for $m_\phi \lesssim 500$ GeV [10,11]. Therefore, the observability for the muon pair discovery channel at the CMS detector will be better than what is shown in this letter.

In Figure 2 we show the cross section of muon pairs from Higgs decays along with a bottom quark, $\sigma(pp \to bA^0 + X \to b\mu^+\mu^- + X)$, for $\tan\beta = 10$ and 50, with a common mass for scalar quarks, scalar leptons and the gluino $m_{\tilde{q}} = m_{\tilde{g}} = \mu = 1$ TeV. We also present the background cross sections in the mass window of $m_A \pm \Delta M_{\mu^+\mu^-}$ for the SM processes $pp \to b\mu^+\mu^- + X$, $pp \to j\mu^+\mu^- + X$, and $pp \to b\bar{b}W^+W^- + X$. The cuts, tagging efficiencies, and K factors discussed above are included. There are a couple of things to note from this figure.

(a) For an integrated luminosity of 30 fb^{-1}, the cross section of the Higgs signal with $\tan\beta \sim 50$ can be much larger than that of the physics background after acceptance cuts. The SM subprocesses $gg \to b\mu^+\mu^-$ and $q\bar{q} \to b\mu^+\mu^-$ make the major contributions to the physics background for $M_{\mu^+\mu^-} \lesssim 180$ GeV, but $gg \to b\bar{b}W^+W^-$ and $q\bar{q} \to b\bar{b}W^+W^-$ become the dominant background for higher muon pair invariant mass.

(b) At the higher luminosity of 300 fb^{-1}, $gg \to b\bar{b}W^+W^-$ and $q\bar{q} \to b\bar{b}W^+W^-$ make up the dominant background for $M_{\mu^+\mu^-} \gtrsim 120$ GeV. The higher p_T cut on the $b-$quark reduces the Higgs signal, while the larger allowed missing E_T make the $bbWW$ background greater than the Higgs signal with $\tan\beta \lesssim 50$.

We define the signal to be observable if the lower limit on the signal plus background is larger than the corresponding upper limit on the background [34,35], namely,

$$L(\sigma_s + \sigma_b) - N\sqrt{L(\sigma_s + \sigma_b)} > L\sigma_b + N\sqrt{L\sigma_b} \tag{1}$$

which corresponds to

$$\sigma_s > \frac{N^2}{L}\left[1 + 2\sqrt{L\sigma_b}/N\right] \tag{2}$$

Here L is the integrated luminosity, σ_s is the cross section of the Higgs signal, and σ_b is the background cross section. Both cross sections are taken to be within a bin of width $\pm\Delta M_{\mu^+\mu^-}$ centered at m_ϕ. In this convention, $N = 2.5$ corresponds to a 5σ signal. We take the integrated luminosity L to be 30 fb^{-1} and 300 fb^{-1} [12].

For $\tan\beta \gtrsim 10$, m_A and m_H are almost degenerate when $m_A \gtrsim 125$ GeV, while m_A and m_h are very close to each other for $m_A \lesssim 125$ GeV in the MSSM. Therefore, when computing the discovery reach, we add the cross sections of the A^0 and the h^0 for $m_A < 125$ GeV and those of the A^0 and the H^0 for $m_A \geq 125$ GeV [10–12].

Figure 3 shows the 5σ discovery contours for the MSSM Higgs bosons where the discovery region is the part of the parameter space above the contour. We have chosen $M_{\rm SUSY} = m_{\tilde{q}} =$

$m_{\tilde{g}} = m_{\tilde{\ell}} = \mu = 1$ TeV. If $M_{\rm SUSY}$ is smaller, the discovery region of $A^0, H^0 \to \mu^+\mu^-$ will be slightly reduced for $m_A \gtrsim 250$ GeV, because the Higgs bosons can decay into SUSY particles [36] and the branching fraction of $\phi^0 \to \mu^+\mu^-$ is suppressed. For $m_A \lesssim 125$ GeV, the discovery region of $H^0 \to \mu^+\mu^-$ is slightly enlarged for a smaller $M_{\rm SUSY}$, but the observable region of $h^0 \to \mu^+\mu^-$ is slightly reduced because the lighter top squarks make the H^0 and the h^0 lighter; also the $H^0 b\bar{b}$ coupling is enhanced while the $h^0 b\bar{b}$ coupling is reduced [10,14].

V. Conclusions

The muon pair decay mode is a promising channel for the discovery of the neutral Higgs bosons in the minimal supersymmetric model at the LHC. The A^0 and the H^0 should be observable in a large region of parameter space with $\tan\beta \gtrsim 10$. In particular, Fig. 3 shows that the associated final state of $b\phi^0 \to b\mu^+\mu^-$ could discover the A^0 and the H^0 at the LHC with an integrated luminosity of 30 fb^{-1} if $m_A \lesssim 600$ GeV. At a higher luminosity of 300 fb^{-1}, the discovery region in m_A is expanded up to $m_A \lesssim 800$ GeV for $\tan\beta \sim 50$. This discovery channel with one energetic bottom quark extends the discovery potential of the LHC beyond the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$.

The excellent muon mass resolution of the CMS and the ATLAS detectors will be important for Higgs searches at the LHC. For large $\tan\beta$, the muon pair discovery mode might be the only channel at the LHC that allows precise reconstruction of the A^0 and the H^0 masses. The discovery of the associated final states of $b\phi^0 \to b\mu^+\mu^-$ and $b\bar{b}\phi^0 \to b\bar{b}\mu^+\mu^-$ will provide information about the Yukawa couplings of $b\bar{b}\phi^0$ and an opportunity to measure $\tan\beta$. The discovery of both $\phi^0 \to \tau\bar{\tau}$ and $\phi^0 \to \mu^+\mu^-$ will allow us to understand the Higgs Yukawa couplings with the leptons.

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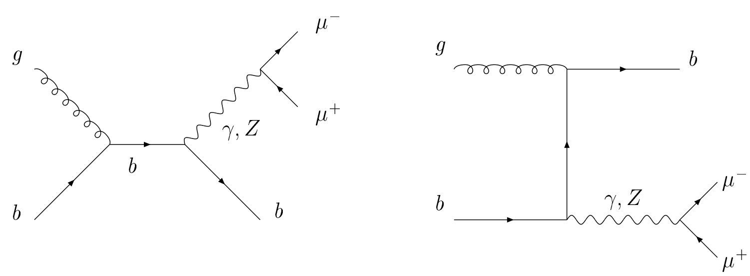

FIG. 1. Feynman diagrams for the background from $bg \to b\mu^+\mu^-$.

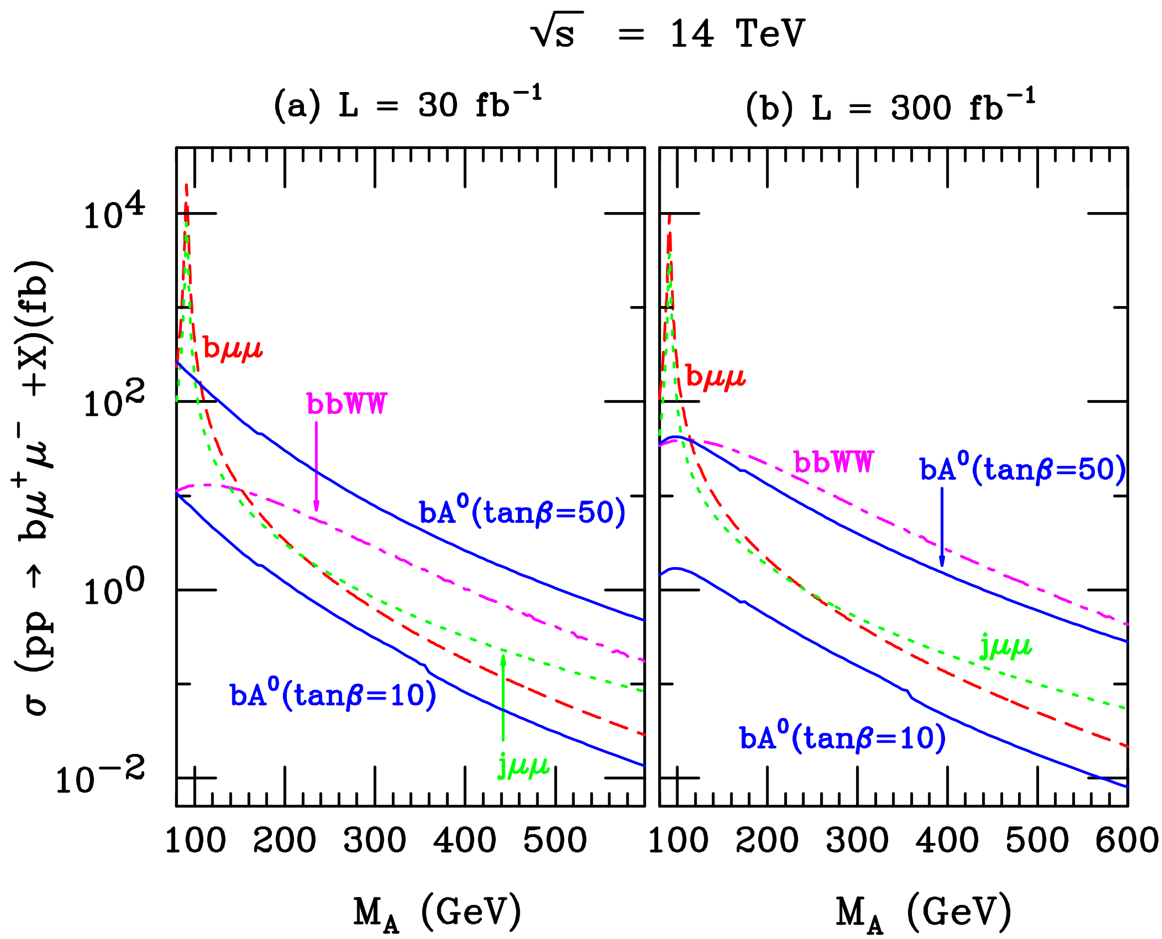

FIG. 2. The cross section of $pp \to bA^0 + X \to b\mu^+\mu^- + X$, $b = b$ or $\bar{b}$, at the LHC, as a function of m_A, for $m_{\tilde{q}} = m_{\tilde{g}} = \mu = 1$ TeV and $\tan\beta = 10$ or 50. Also shown are the background cross sections in the mass window of $m_A \pm \Delta M_{\mu^+\mu^-}$ as discussed in the text for the SM processes $pp \to b\mu^+\mu^- + X, b = b$ or $\bar{b}$, (dashed), $pp \to j\mu^+\mu^- + X, j = g, u, d, s, c$ (dotted), and $pp \to b\bar{b}W^+W^- + X$ (dot-dashed). We have applied K factors, acceptance cuts, and efficiencies of b tagging and mistagging.

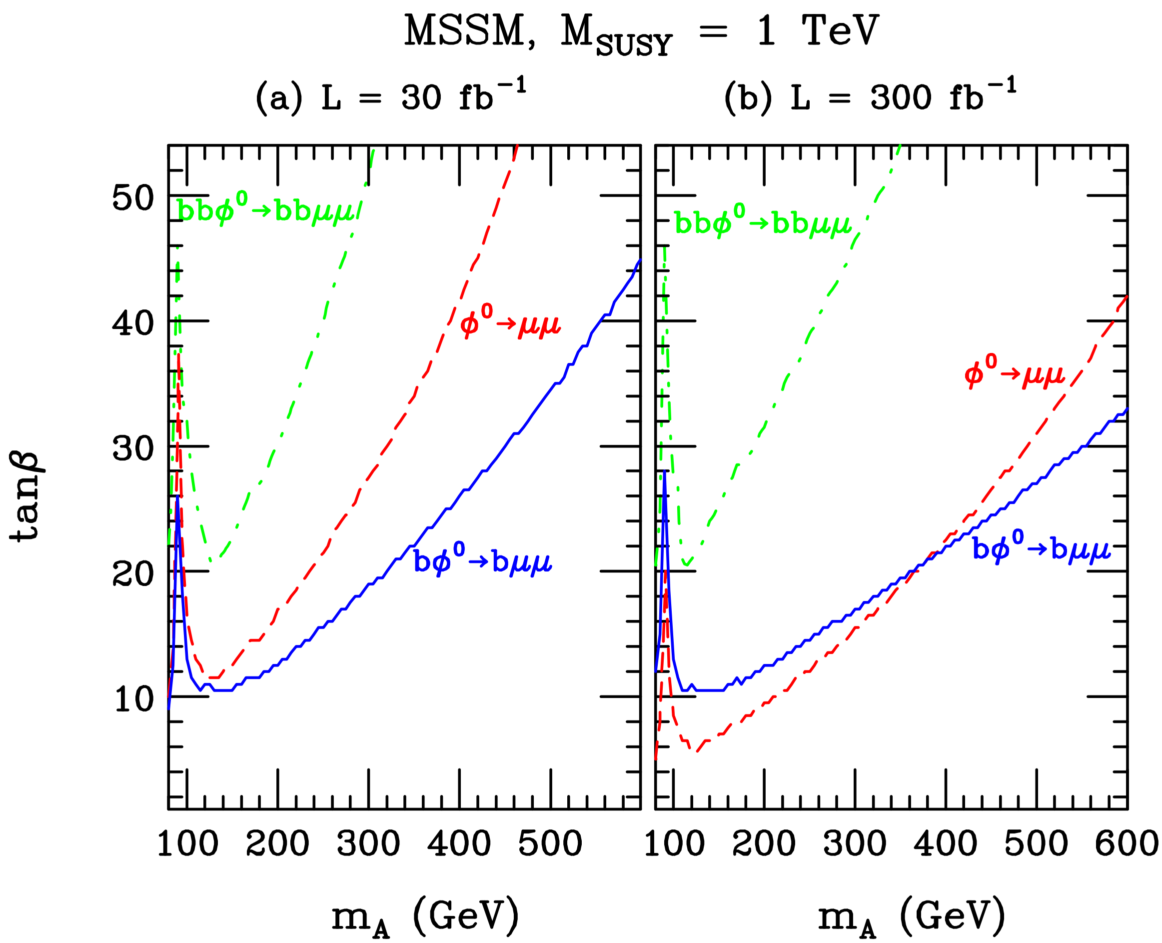

FIG. 3. The 5σ discovery contours at the LHC for an integrated luminosity (L) of 30 fb^{-1} and 300 fb^{-1} in the m_A versus $\tan\beta$ plane. The signal includes $\phi^0 = A^0$ and h^0 for $m_A < 125$ GeV, and $\phi^0 = A^0$ and H^0 for $m_A \geq 125$ GeV. The discovery region is the part of the parameter space above the contours.